Complementarity of LAr and Water Cerenkov

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At the April 2008 DUSEL Workshop in Lead, S.D. it was brought up that it would be useful to have a document on the physics complementarity of the Liquid Argon TPC and Water Cerenkov detectors for the following processes:

1. Nucleon decay,

2. Relic supernova neutrinoes (extra-galactic),

3. Galactic supernova neutrinoes,

4. Long-baseline neutrino beam.

I became interested in starting this document, not because I am an expert in any of 1-4, but because I am not an expert, and thus would learn a lot, and also, because I see it through the eyes of a non-expert. Everything that will be presented is not from my own work, and I will try to give the references. This document is written for the non-expert, ie. a knowledgeable physicist not yet involved in 1-4.

The Liquid Argon TPC measures ionization. A plot of dE/dx from the PDG is shown in Fig. 1. The water detector measures Cerenkov light. A plot of the intensity of water Cerenkov light is shown in Fig. 2. One should see the talks for detailed information on the detector optimization, etc. The best limits on nucleon decay come from the SuperK detector - see Table 1. The largest Liquid Argon TPC built so far is Icarus. This is a 0.6kton detector located in the Gran Sasso Lab - see Dave Cline's talk. The LAr detector is not yet large enough to have an impact on nucleon decay. The limits on nucleon decay from the PDG are given in Appendix 1. The most stringent limit comes from a decay mode with a large decay momentum of 459 MeV/c and electro-magnetic showers: the decay $p \rightarrow e^+ \pi^0$ has an excellent lifetime limit of 1.6×10^{33} years. Nucleon decay modes with small momentum and non-electromagnetic showers have much poorer limits, typically one to two orders of magnitude less. This is where a LAr TPC would have the greatest impact, since the LAr detector measures ionization all the way down to zero momentum. Thus, although the LAr detector mass will almost certainly be less than the water Cerenkov detector mass, since LAr costs more than water, etc., LAr and water Cerenkov detectors are still very complementary for the physics of nucleon decay.
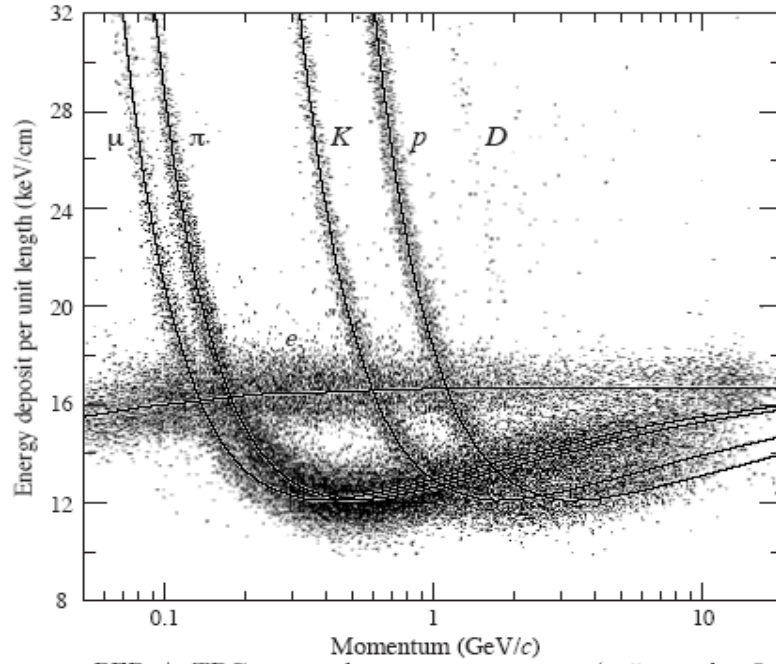
Figure 28.6: PEP4/9-TPC energy-deposit measurements (185 samples @8.5 atm Ar-CH$_4$ 80–20%) in multihadron events. The electrons reach a Fermi plateau value of 1.4 times the most probably energy deposit at minimum ionization. Muons from pion decays are separated from pions at low momentum; π/K are separated over all momenta except in the cross-over region. (Low-momentum protons and deuterons originate from hadron-nucleus collisions in inner materials such as the beam pipe.)
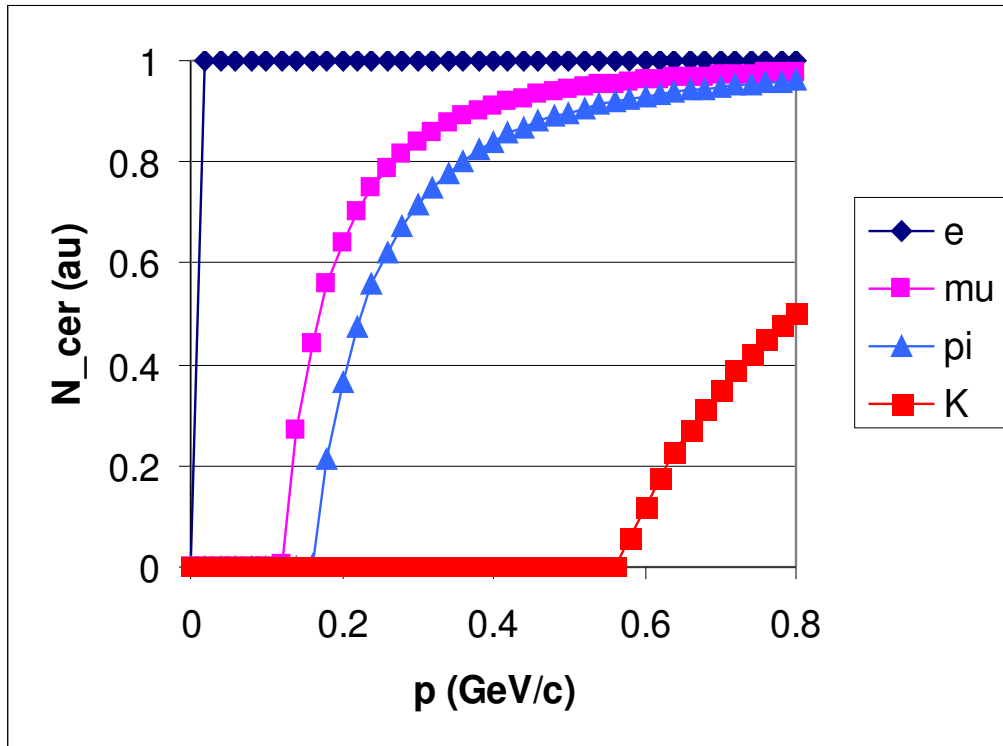

Fig. 2. Cerenkov light vs. momentum.

Table 1. Some SuperK detector parameters.

Detector	**Water Cerenkov with PMTs**
Total Water Mass	50 kton
Fiducial mass for proton decay	22.5 kton
Tank	Welded stainless steel
Tank diameter	39 m
Tank height	42 m
Mine depth	1 km (2.7km water equiv.)

Next we turn to relic supernova neutrinoes. This is the sum over all supernova neutrinoes over all space time at our event horizon (see Fig. 3). This obviously excludes neutrinoes from supernova from our galaxy, which passed by us in 1987, for example.

The feeble signal of all SNe

- Sum over the whole universe:

$$\sum_{\star} \Phi^{\star}_{\nu}$$
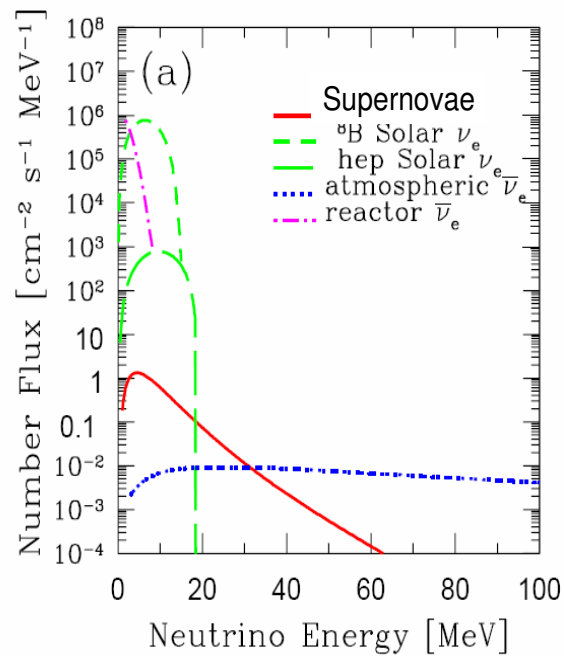
S. Ando and K. Sato, New J.Phys.6:170,2004.

Fig. 3. Relic supernova neutrino flux from Cecelia Lunardini's beautiful theory talk. Reactor anti-neutrinoes are negligible in South Dakota.

Theoretical Supernova Relic Neutrino Flux Spectra

Population synthesis (Totani et al., 1996)
Constant supernova rate (Totani et al., 1996)
Cosmic gas infall model (R.A. Malaney, 1997)
Cosmic chemical evolution (Hartmann et al., 1997)
Heavy metal abundances (Kaplinghat et al., 2000)
LMA oscillation (Ando et al., 2002)

Neutrino Flux per sq-cm per second per MeV

Neutrino Energy (MeV)

Relic ν in Super-K

spallation products from cosmic μ's

atm. $\nu_\mu \to$ stealth $\mu^\pm \to e^\pm$

relic $\bar{\nu}$'s

events

MeV

SUPERKAMIOKANDE

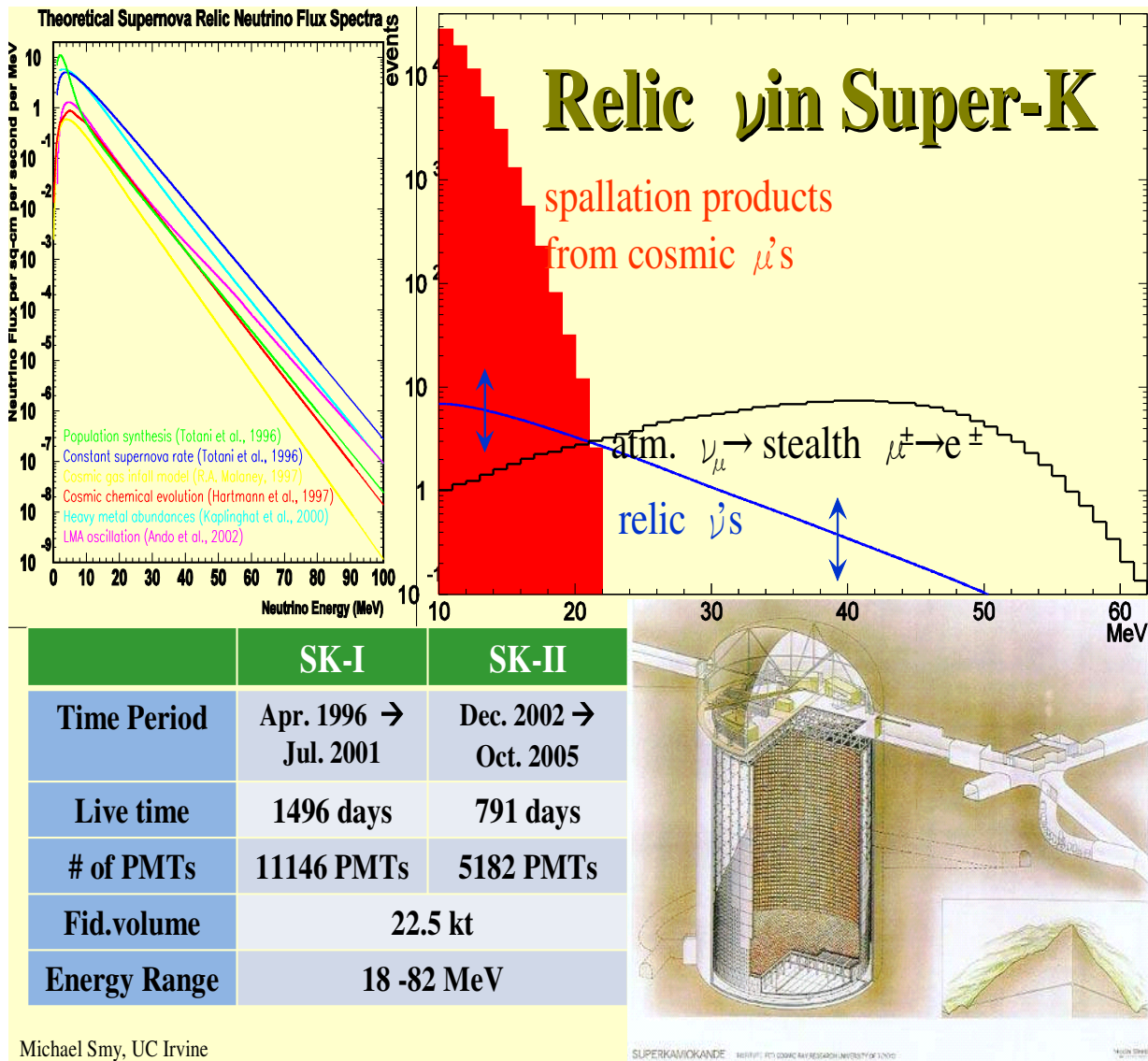|	SK-I	SK-II
Time Period	Apr. 1996 → Jul. 2001	Dec. 2002 → Oct. 2005
Live time	1496 days	791 days
# of PMTs	11146 PMTs	5182 PMTs
Fid. volume	22.5 kt	
Energy Range	18 -82 MeV	

Fig. 4. SuperK relic supernova neutrino signal and experimental backgrounds from Mike Smy's talk.

    Fig. 4 upper left shows the theoretical predictions, which depend on the modeling of the star formation rates. Fig. 4 upper right shows the expected signal and experimental backgrounds for the SuperK detector. Stealth muons are muons produced from atmospheric neutrinoes which are below Cerenkov threshold, and which then stop in the detector and decay $\mu \to e \, \upsilon \, \upsilon$. Spallation products from cosmic muons can be reduced by going deeper than SuperK (see Fig. 5), or by adding Gd salt (see Mike's talk). The Ray Davis detector depth (4850 ft = 1.5km) will reduce the cosmic muon rate by about an order of magnitude compared to the SuperK depth.
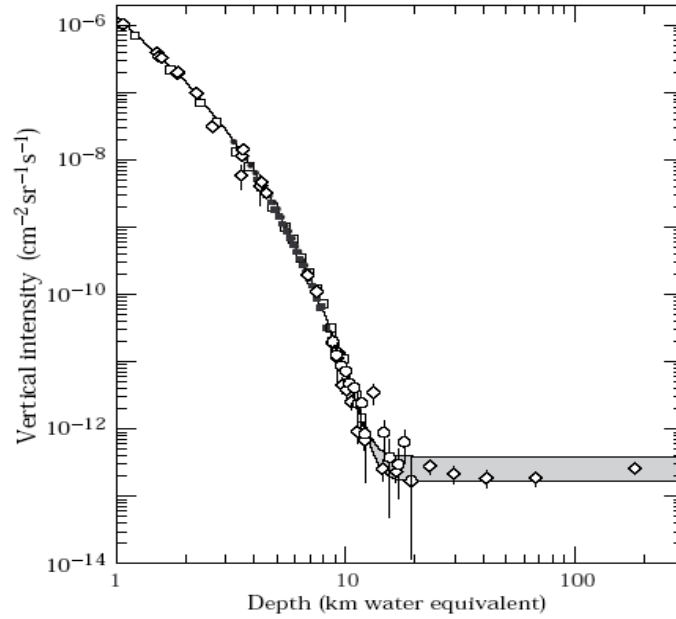
Figure 24.5: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: $\diamond$: the compilations of Crouch [45], $\square$: Baksan [46], $\circ$: LVD [47], $\bullet$: MACRO [48], $\blacksquare$: Frejus [49]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

Fig. 5. Vertical muon intensity (μ/cm^2 s sr) vs. depth from PDG.

- Background:
  - Solar
  - Atmospheric
  - Energy window: 16-40 MeV (normalization-dependent)

- 0.5 Mt £ year:
  - N » 60
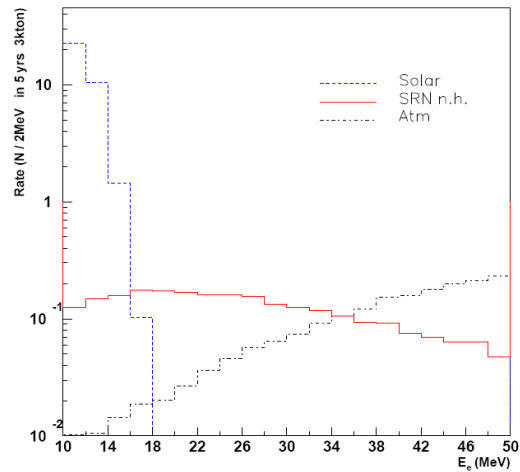
Cocco et al., JCAP 0412:002,2004

Fig. 6. LAr detector for relic supernova neutrinoes showing the physics backgrounds from solar and atmospheric neutrinoes from Cecelia Lunardini's talk. The detector backgrounds are negligible.

A LAr detector would be very complimentary (see Fig. 6). This is because while water is sensitive mainly to anti-electron neutrino charge current interactions for the supernova neutrino energy range, LAr is sensitive mainly to electron neutrino charged current and neutral current interactions (see Fig. 7). The former is due to the physics of the argon nucleus, and the latter because it is an ionization detector and not a Cerenkov detector.
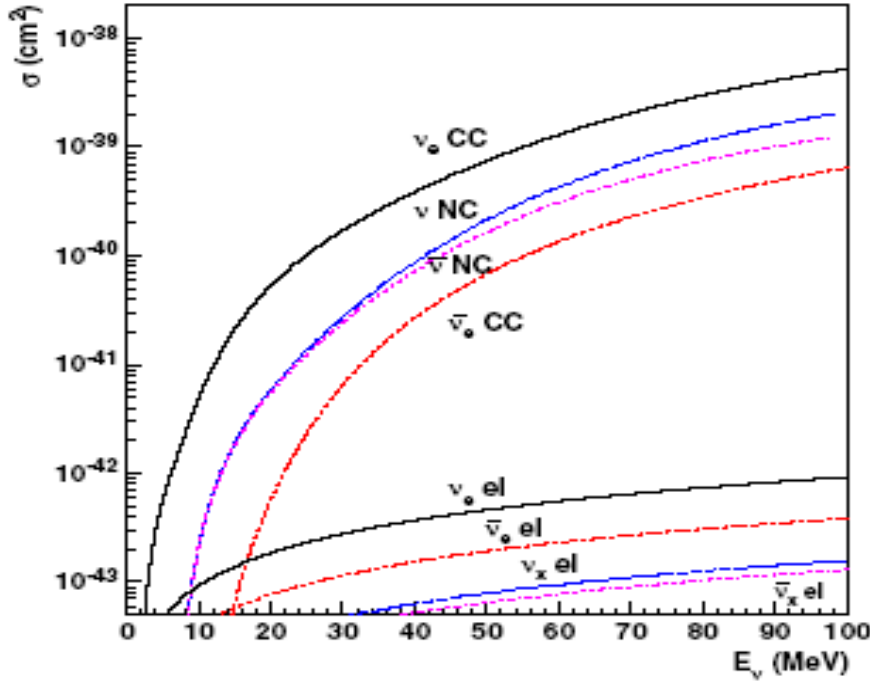

Fig. 7. Neutrino cross-sections in Argon from A.G. Cocco et al. (see Fig.6).

Next we turn to a supernova within our galaxy, which happens every thirty to forty years, on average. We get a very large number of neutrino interactions in a short period of time, so backgrounds are not as important an issue. As discussed above, the water Cerenkov detector sees mainly anti-electron neutrino charged current events, while the LAr detector sees mainly electron neutrino charged current and neutral current events. It would be good to have a measure of both in order to untangle the supernova MSW effects, etc. Thus once again, the LAr and water Cerenkov detectors are very complementary.

Finally, we turn to long baseline neutrino detectors. The energy distribution of the long baseline neutrino beam from FNAL to DUSEL is shown in Fig. 8 from Mary Bishai's talk. For background reasons, the water Cerenkov analysis uses only the quasi-elastic charged current channels. This is fairly clean at the lower energies in Fig. 8, but not at the higher energies. The LAr TPC uses all the charged current channels, and has negligible backgrounds, but, of course, lower mass than the water Cerenkov detector. The LAr TPC will also measure the neutral current events, but not, of course, the neutrino energy. Never the less, this will tell us the total number of neutrinoes of all flavors

incident on the detector, which is a good sanity check. Thus both techniques together would give a really robust result.
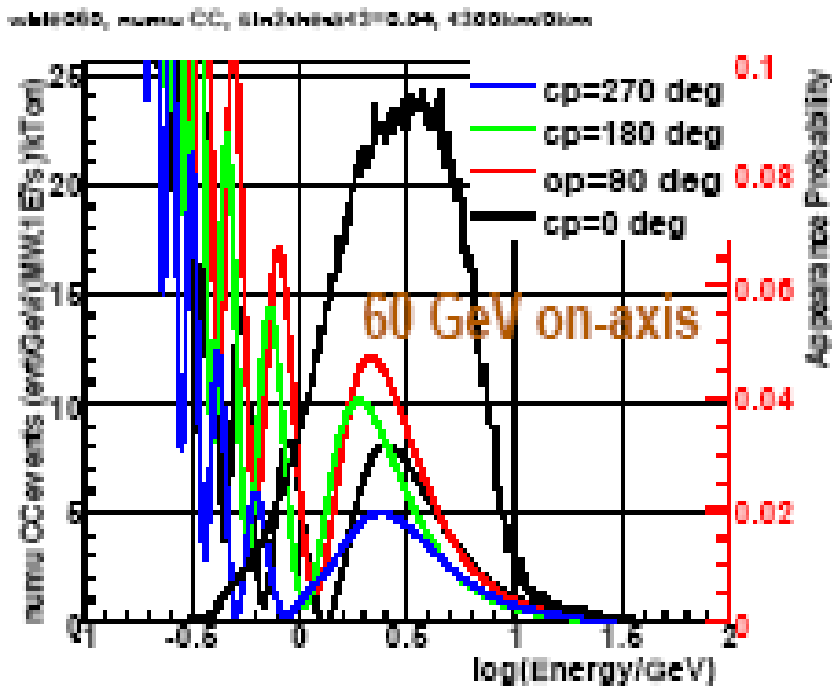

Fig. 8. Long baseline beam from Mary's talk.

   In conclusion, the LAr and water Cerenkov detectors have excellent physics complementarity. One should see the detailed talks for the R&D needed to solve the technical issues on how to build these very massive detectors. As to depth, we discussed above why if you want to do an order of magnitude better than SuperK with a water Cerenkov detector, it should be deeper than SuperK. The Ray Davis depth of 4850 ft seems reasonable. The LAr detector, with the excellent background rejection, could be at a shallower depth. However, Dave Cline in his talk pointed out a physics background: $K\Lambda$ production from cosmic muons. This will be addressed in a separate White Paper.

Appendix I - Limits on Nucleon Decay from PDG

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level	p (MeV/c)
Antilepton + meson			
$N \to e^+ \pi$	> 158 (n), > 1600 (p)	90%	459
$N \to \mu^+ \pi$	> 100 (n), > 473 (p)	90%	453
$N \to \nu \pi$	> 112 (n), > 25 (p)	90%	459
$p \to e^+ \eta$	> 313	90%	309
$p \to \mu^+ \eta$	> 126	90%	297
$n \to \nu \eta$	> 158	90%	310
$N \to e^+ \rho$	> 217 (n), > 75 (p)	90%	149
$N \to \mu^+ \rho$	> 228 (n), > 110 (p)	90%	113
$N \to \nu \rho$	> 19 (n), > 162 (p)	90%	149
$p \to e^+ \omega$	> 107	90%	143

$p \to \mu^+ \omega$	> 117	90%	105
$n \to \nu \omega$	> 108	90%	144
$N \to e^+ K$	$> 17\ (n),\ > 150\ (p)$	90%	339
$p \to e^+ K^0_S$	> 120	90%	337
$p \to e^+ K^0_L$	> 51	90%	337
$N \to \mu^+ K$	$> 26\ (n),\ > 120\ (p)$	90%	329
$p \to \mu^+ K^0_S$	> 150	90%	326
$p \to \mu^+ K^0_L$	> 83	90%	326
$N \to \nu K$	$> 86\ (n),\ > 670\ (p)$	90%	339
$n \to \nu K^0_S$	> 51	90%	338
$p \to e^+ K^*(892)^0$	> 84	90%	45
$N \to \nu K^*(892)$	$> 78\ (n),\ > 51\ (p)$	90%	45

Antilepton + mesons

$p \to e^+ \pi^+ \pi^-$	> 82	90%	448
$p \to e^+ \pi^0 \pi^0$	> 147	90%	449
$n \to e^+ \pi^- \pi^0$	> 52	90%	449
$p \to \mu^+ \pi^+ \pi^-$	> 133	90%	425
$p \to \mu^+ \pi^0 \pi^0$	> 101	90%	427
$n \to \mu^+ \pi^- \pi^0$	> 74	90%	427
$n \to e^+ K^0 \pi^-$	> 18	90%	319

Lepton + meson

$n \to e^- \pi^+$	> 65	90%	459
$n \to \mu^- \pi^+$	> 49	90%	453
$n \to e^- \rho^+$	> 62	90%	150
$n \to \mu^- \rho^+$	> 7	90%	114
$n \to e^- K^+$	> 32	90%	340
$n \to \mu^- K^+$	> 57	90%	330

Lepton + mesons

$p \to e^- \pi^+ \pi^+$	> 30	90%	448
$n \to e^- \pi^+ \pi^0$	> 29	90%	449
$p \to \mu^- \pi^+ \pi^+$	> 17	90%	425
$n \to \mu^- \pi^+ \pi^0$	> 34	90%	427
$p \to e^- \pi^+ K^+$	> 75	90%	320
$p \to \mu^- \pi^+ K^+$	> 245	90%	279

Antilepton + photon(s)

$p \to e^+ \gamma$	> 670	90%	469
$p \to \mu^+ \gamma$	> 478	90%	463
$n \to \nu \gamma$	> 28	90%	470
$p \to e^+ \gamma \gamma$	> 100	90%	469
$n \to \nu \gamma \gamma$	> 219	90%	470

Three (or more) leptons

$p \rightarrow e^+ e^+ e^-$	> 793	90%	469
$p \rightarrow e^+ \mu^+ \mu^-$	> 359	90%	457
$p \rightarrow e^+ \nu \nu$	> 17	90%	469
$n \rightarrow e^+ e^- \nu$	> 257	90%	470
$n \rightarrow \mu^+ e^- \nu$	> 83	90%	464
$n \rightarrow \mu^+ \mu^- \nu$	> 79	90%	458
$p \rightarrow \mu^+ e^+ e^-$	> 529	90%	463
$p \rightarrow \mu^+ \mu^+ \mu^-$	> 675	90%	439
$p \rightarrow \mu^+ \nu \nu$	> 21	90%	463
$p \rightarrow e^- \mu^+ \mu^+$	> 6	90%	457
$n \rightarrow 3\nu$	> 0.0005	90%	470